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Performance evaluation and optimization of steam generating systems

■ **C.S. BALADHIYA AND J.S. DOSHI**

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See end of the Paper for authors' affiliation

Correspondence to :

C.S. BALADHIYA
College of Agriculture, Anand Agricultural University, JABUGAM (GUJARAT) INDIA
Email : csbaladhiya@gmail.com

■ **ABSTRACT :** Steam is widely used as heating medium for thermal processing of dairy and food products. Steam is produced in boiler using various types of fuels such as coal, fuel oil, natural gas, biogas etc. In the wake of the tremendous rise in fuel price and decline in the fuel supply in the recent year, there is a need of economizing the energy utilization. The efficient generation of steam depends mainly on regular monitoring of operating parameters such as combustion process, excess air control, water treatment, regular maintenance, monitoring of flue gas temperature etc. The knowledge of various parameters affecting the performance is a basic requirement for the optimization of the steam generating system. The automatic controls used in modern boilers have improve the efficiency of boiler by optimizing operating parameters required for efficient combustion process and to achieve safety in operation of fuels. Operation of boiler under optimum conditions not only helps in reducing the cost of steam generation but also helps in reducing the air pollution.

■ **KEY WORDS :** Boiler, Steam, Energy management, Fuel

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Thermal energy is one of the very important requirements for many industries. Steam is widely used as heating medium for thermal processing of dairy and food products. Steam is produced in boiler using various types of fuels such as coal, fuel oil, natural gas, biogas etc. It has been estimated that two-third of the total fuel oil is used for the generation of steam in various industries in India. Electrical power plants in India consumes more than 60 per cent of thermal energy for raising steam for operating steam turbines and during the next decade this figure is expected to grow. The energy management has become very important necessity in the present era of uncertainties in availability of fuel, increasing cost of fuel, worldwide competition and concern for environment control (Miroslav *et al*., 2012). The importance of energy conservation in boiler has been emphasized by many scientists in order to contribute towards conservation of nation's fuel reserves and to reduce the import of fuels (Upadhyay, 1998). The performance evaluation and optimization of steam generating system is not only important to reduce the cost of steam generation but also helps in reducing the emissions of Green House Gases in the environment. It is also reported that about 40-50 per cent of the total energy used in dairy plants is heat energy for the processing and manufacture of dairy products (Harries, 1982 and Slinker, 1981). The performance of boilers depends on several factors such as combustion efficiency, quantity of excess air, temperature of flue gas, etc. and optimization of all operating parameters is

very essential to achieve higher efficiency of steam generating systems. Automation employed in the modern boiler has help a lot in achieving optimum boiler performance and safety with minimum adverse effect on environment.

Types of steam generating systems :

Steam generators are classified as horizontal, vertical and inclined depending on alignment of axis of boiler; fire tube and water tube boilers based on the flow of water and hot flue gases through the boiler; externally fired and internally fired boilers based on the location of furnace; forced circulation and natural circulation boilers depending on the mode of circulation of water and high pressure and low pressure boilers depending on the pressure of steam produced (Pandya and Shah, 1984; Dodeja and Dabas, 2009; *www.energymanagert-raining. com; www.brighthubengineering.com*). The classification of boilers based on the use, configuration, types of fuel used etc. also have been reported (*www.uswitch.com; ftp://ftp.energiaq.bme.hu*). In dairy plants, low pressure fire tube horizontal boilers are widely used as these boilers are easy to operate and maintain.

Capacity of boilers :

The capacity of boilers or steam generating systems is defined as the amount of steam produced in unit time from water at 100° C to steam at 100° C or under any specified conditions. It is expressed as kg steam per hour for small size boilers and tons of steam per hour for large capacity boilers. Earlier, it was expressed as boiler house power which is equivalent to an evaporation of 15.653 kg water per hour from and at 100° C (Pandya and Shah, 1984). Boilers are available from very small capacity of 100 kg steam per hour to 10000 kg steam per hour. The operating pressure varies from 5 to 20 bar for heating requirements in dairy plants while power plant boilers operate above 80 bar pressure. The capacity of boiler is estimated based on the consumption of steam for various unit operations and operational schedule of these operations.

Performance of boiler :

The performance of boiler is expressed as efficiency of boiler which is the ratio of output energy (amount of heat used for the generation of steam) to the input energy (amount of heat supplied). It varies between 80 to 88 per cent for a modern boilers. Equivalent evaporation is also used to compare the performance of boilers when the operating conditions are different for various boilers (Khandare, 2008). The performance of boilers is affected by various factors such as combustion efficiency, maintenance, quality of water, operating conditions of boilers etc. The efficiency of boiler and effect of various operating parameters on the performance of boiler have been reported (Anonymous, 2007; *www.cleaverbrooks. com*). Steam is produced by combustion of various fuels and hence boiler performance may be expressed in term of quantity of steam produced per kg of fuel used for comparing the steam output per unit quantity of fuel used (Miroslav *et al*., 2012 and Tewari *et al*., 2012).

Measurement of boiler performance :

The performance evaluation is one of the very essential requirements for the conservation of energy and optimization of operating parameters of boilers. There are two basic methods of assessing boiler efficiency.

Direct method:

It is based on the measurement of output energy and input energy of fuel. In direct method, efficiency is expressed as the ratio of energy gain of the working fluid (water and steam) to the energy content of the boiler fuel. This is also known as 'input-output method' as it needs only the useful output (steam) and the heat input (*i.e.* fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula given below :

$$\textbf{Boiler efficiency (\%)} = \frac{\textbf{Heat output}}{\textbf{Heat input}} \times 100$$

This method is relatively simple as it requires the measurement of rate of steam generated and the operating pressure of the boiler. The input energy can be obtained by measurement of rate of fuel used and its calorific value. However, this method does not give clues regarding the reasons for losses. The details of measurement required for this method are described (Pandya *et al.*, 2005; Miroslav and Dusan, 2012 and Patel *et al.*, 2013). Bureau of Energy efficiency has suggested to follow British Standards BS845:1987, ASME Standard:PTC-4-1 and Indian Standard IS 8753 method for determining efficiency of boilers (*www.beeindia.in*).

Indirect method :

The efficiency is obtained by subtracting various types of energy losses from 100 in indirect method of determining boiler efficiency. Thus, it is a difference between energy input and the energy losses. This method of estimating boiler efficiency and its advantages over the direct method are described (Durkin, 2006 and Gupta *et al*., 2012). The major heat losses in boiler are through flue gas, due to hydrogen and moisture in fuel, unburnt fuel and radiation losses (Goodall, 1980; Dave and Bhadania, 1981; Patel *et al.*, 2013; Nagar *et al.*, 2013 and Gupta *et al*., 2011).

Factors affecting the performance of boilers:

The efficiency of boiler depends on many factors such as operational parameters, design of boiler, level of automation and maintenance etc. Operation of boiler with higher efficiency over a period of time is also one of the important aspects as efficiency deteriorates owning to aging effects. The factors affecting the performance of a boilers have been discussed (Pandya *et al*., 2005; Keshavarz *et al*., 2010 and Gupta *et al*., 2012).

Fuel specifications:

The types of fuels used in commercial boilers are solids, liquids and gases. The principle constitutes of fuels are carbon and hydrogen which contribute the calorific value of fuels. The various type of fuels and their specifications have been reported (Pandya *et al*., 2005; *www.cleaverbrooks.com*). The specifications of the fuels have considerable effect on efficiency of boilers. The ratio of hydrogen to carbon of a fuel has also impact on the efficiency. For example, gaseous fuels having higher the hydrogen content, the more water vapor is formed during combustion which results into energy loss as the vapor absorbs energy in the boiler and lowers the efficiency. The natural gas has a hydrogen to carbon (H/C) ratio of 0.31 and if H/C ratio of 0.25 is used for calculating efficiency, the value of efficiency increases from 82.7 per cent to 83.9 per cent (Bhatia, 2012). The properties of fuel such as moisture content, ash content in case of solid fuels and viscosity and impurities in case of liquid fuels are also important parameter affecting the performance of boilers.

Heat content of fuel:

The heat content of fuel is expressed as Gross Calorific Value (GCV) or Net Calorific Value (NCV). The total energy available from the fuel is known as GCV while NCV is the energy value of fuel excluding the energy loss in the form of the water vapour in the flue gas. This water vapour is formed by combustion of hydrogen of fuel with oxygen. The knowledge of calorific value is one of the essential requirements for calculation of boiler efficiency. The GCV is about 10-15 per cent higher than NCV and it is assumed that all heat available from the fuel is recovered including latent heat used to form water vapour in the process of combustion of fuels. The calculations of efficiency based on gross calorific value will give maximum obtainable efficiencies much lower than 100 per cent, due to this irrecoverable loss. Both the gross calorific value and net calorific value are equally valid, but for comparison purposes, a particular convention should be used (Bhatia, 2012). The GCV of coal, furnace oil and natural gas varies from 29.3-33.5 MJ/kg (Pandya *et al*., 2005), 40.19 MJ/kg (*www.ces.iisc.ernet.in*) and 40.08 MJ/m^3, respectively (Pandya *et al*., 2005).

Boiler stack temperature:

Boiler stack temperature is the temperature of the combustion gases leaving the boiler. This temperature represents the major portion of the energy not converted to usable output. The higher temperature of flue gases indicates less transfer of energy and lower the boiler efficiency. If a boiler runs on natural gas with a stack temperature of 350°F, the maximum theoretical efficiency of the unit will be 83.5 per cent. For the boiler to operate at 84 per cent efficiency, the stack temperature must be less than 350°F (Bhatia, 2012). Wang (2008) reported that heat is lost from the stack through the hot flue gas and radiation of the hot stack surface. Over 20 per cent of the total heat is normally exhausted from the boiler through the stack without a waste heat recovery unit. The importance of stack temperature in efficiency of boiler has been reported (Pandya and Shah, 1984 and Ahmad, 2006). Low temperature of flue is desirable to get higher efficiency of the boiler. However, it should not be too low which may cause water vapour to condense in the chimney. The flue gas temperature should be above the sulphur acid dew point to prevent corrosion. Flue gas temperature should not be below 160°C and 140°C for oil fired boiler and coal fired boilers, respectively. Generally, in small and medium sized plants,

the flue gas temperature is about 200-250^{0}C at the maximum output. However, lower temperature of flue gases leaving the chimney is desirable.

Excess air levels:

The minimum theoretical quantity of air required, which is known as stoichiometric amount of air for combustion of fuel, can be estimated based on the composition of fuels. The calculation for stoichiometric quantity of air for the complete combustion process have been documented (Pandya *et al.*, 2005). The ratio of amount of air to the quantity of fuelsis known as stoichiometric air to fuel ratio. However, stoichiometric quantity of air is not adequate for the complete combustion of fuels due to improper mixing of air with the fuels in the combustion chamber. Excess air is supplied to the boiler beyond what is required for complete combustion primarily to ensure complete combustion. A certain amount of excess air is provided to the burner as a safety factor for sufficient supply of oxygen for combustion of fuels (Bhatia, 2012). The amount of excess air required for boiler depend on types of fuel and efficiency of burner/combustion chamber. Kamalnayan and Krishnamurthy (2002) found that inadequate supply of air caused inefficient combustion and less boiler efficiency. Hence, optimum quantity of air is very essential for better overall efficiency of boiler. The optimum level of excess air is to be maintained to get optimum efficiency. Higher level of excess air causes reduction in efficiency of the boiler due to higher amount of heat loss in the flue gases. Oxygen analyzer is used to measure the oxygen level in the flue gas to monitor the quantity of the excess air. Automatic controls to monitor the amount of air based on the measurement of oxygen in the flue gas is used in modern boilers.

Ambient air temperature and relative humidity:

Ambient air temperature and relative humidity have effect on boiler efficiency. Most efficiency calculations use an ambient temperature of 80°F and a relative humidity of 30 per cent. Higher temperature of the air and lower relative humidity are desirable for getting higher efficiency of the boiler. Bhatia (2012) has reported that efficiency changes more than 0.5 per cent for every 20°F change in ambient temperature and relative humidity has also shown similar effect. The effect of ambient conditions on the boiler performance has been discussed (Elshamy, 2006 and Mehdi and Amir, 2012).

Optimization of boiler efficiency :

Optimization of boiler performance can be achieved by operational management of boiler and effective maintenance programme of the boilers. The following aspects are important for the optimization of boilers in order to conserve the energy (Bujak, 2009; *http://www.energymanagertraining.com*).

– Stack temperature control
– Use of efficient economizer
– Provision of air preheater
– Controlling radiation and convection heat losses
– Adoption of automation for blow down control
– Regular maintenance of heat transfer surfaces
– Selection of appropriate type of boiler and capacity
– Adoption of variable speed controls for monitoring speed of blowers and pumps
– Treatment of water
– Proper scheduling of boilers
– Excess air control

Automation for optimization of boiler performance:

The various types of automatic controls used in industrial boiler have greatly helped to improve the efficiency of boiler by optimizing the combustion process and achieving stringent standards for emissions. The safety requirements in operation of boiler can be accomplished with the automatic controls. The different boiler manufacturers have reported the use of various types of automatic controls depending on the capacity, types of fuels used, safety requirements, etc. The use of PLC-SCADA based automatic controls for operation of boiler (Lakhoua and Jbira, 2012) and precise control of combustion optimization and safety interlocking have been reported (*www.spirexsarco.com*). The major controls commonly used in boiler are automation stating and shutdown, water level control, pressure control, combustion control, temperature controls at various points, TDS control, automatic blow down, warning alarm etc.

Conclusion :

In the wake of the tremendous rise in fuel price and decline in the fuel supply in the recent year, there is a need of economizing the energy utilization. The efficient

generation of steam depends mainly on regular monitoring of operating parameters such ascombustion process, excess air control, water treatment, regular maintenance, monitoring of flue gas temperature etc. The knowledge of various parameters affecting the performance is a basic requirement for the optimization of the steam generating system. The automatic controls used in modern boilers have improve the efficiency of boiler by optimizing operating parameters required for efficient combustion process and to achieve safety in operation of fuels. Operation of boiler under optimum conditions not only helps in reducing the cost of steam generation but also helps in reducing the air pollution.

Authors' affiliations:
J.S. DOSHI, Regional Research Station (A.A.U.), ANAND (GUJARAT) INDIA

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